0797

WATER RESOURCES RESEARCH, VOL. 17, NO. 4, PAGES 1133–1138, AUGUST 1981

Canopy Temperature as a Crop Water Stress Indicator

R. D. JACKSON, S. B. IDSO, R. J. REGINATO, AND P. J. PINTER, JR.

U.S. Water Conservation Laboratory, Phoenix, Arizona 85040

Canopy temperatures, obtained by infrared thermometry, along with wet- and dry-bulb air temperatures and an estimate of net radiation were used in equations derived from energy balance considerations to calculate a crop water stress index (CWSI). Theoretical limits were developed for the canopy-air temperature difference as related to the air vapor pressure deficit. The CWSI was shown to be equal to $1 - E/E_p$, the ratio of actual to potential evapotranspiration obtained from the Penman-Monteith equation. Four experimental plots, planted to wheat, received postemergence irrigations at different times to create different degrees of water stress. Pertinent variables were measured between 1340 and 1400 each day (except some weekends). The CWSI, plotted as a function of time, closely paralleled a plot of the extractable soil water in the 0- to 1.1-m zone. The usefulness and limitations of the index are discussed.

INTRODUCTION

Plant temperature has long been recognized as an indicator of water availability [*Gates*, 1964; *Wiegand and Namken*, 1966]. Until infrared thermometers became available, most plant temperature measurements were made with contact sensors on, or embedded in, leaves [e.g., *Ehrler*, 1973]. *Monteith and Szeicz* [1962] and *Tanner* [1963] were among the first to use infrared thermometry to determine plant temperatures. *Tanner* [1963] stated that 'plant temperature may be a valuable qualitative index to differences in plant water regimes.' During the past decade, infrared technology has progressed to the point that lightweight (≃1 kg) hand-held infrared thermometers, accurate to 0.5°C, are available for routine use. The rapidity of measurement and the ability to average the temperature of all plant parts within the field of view (FOV) of the instrument make these devices ideal for crop canopy temperature measurements.

Ehrler [1973] used thermocouples embedded in cotton leaves to determine leaf temperatures. His results showed that the leaf-air temperature differences decreased after irrigation, reached a minimum several days later, and then increased as the soil water became limiting. His data indicated that a linear relationship exists between the leaf-air temperature difference and the vapor pressure deficit of the air. He concluded that using leaf-air temperature differences for scheduling irrigations in cotton has merit and should be developed.

Idso et al. [1977] and *Jackson et al.* [1977] used the canopy temperature T_c (as measured by infrared thermometry) minus the air temperature T_A as an index of crop water status. They called the difference $T_c - T_A$ the 'stress-degree-day' and related this parameter to yield and water requirements. Because they were concerned with developing a technique to evaluate crop water stress remotely (with a minimum number of measurements), they assumed that environmental factors such as vapor pressure deficit, net radiation, and wind would be largely manifested in the temperature difference. Experience has shown that his assumption is not too restricting in some cases but is severely restricting in others. Recently, *Idso et al.* [1981*a*] presented $T_c - T_A$ and vapor pressure deficit (VPD) data for several crops and showed that the relationship between $T_c - T_A$ and VPD, for well-watered crops under clear sky conditions, was linear, as *Erhler* [1973] had suggested. They used a line obtained by linear regression on these data as a lower limit, and an upper limit assumed to hold for nontranspiring crops, to define a crop water stress index (CWSI). They suggest that this index is a reasonably quantitative evaluator of crop water stress and, in situations where vapor pressure deficit data are available, should be used in place of the stress-degree-day.

In this report we review energy balance considerations to show how $T_c - T_A$ is related to VPD and net radiation and present a theoretical basis for the crop water stress index. The approximations necessary for the development of an operational, rapid means of assessing crop water stress on an areal basis are discussed.

ENERGY BALANCE CONSIDERATIONS

The energy balance for a crop canopy can be written as

$$R_n = G + H + \lambda E \qquad (1)$$

where R_n is the net radiation (W m^{-2}), G is the heat flux below the canopy (W m^{-2}), H is the sensible heat flux (W m^{-2}) from the canopy to the air, and λE is the latent heat flux to the air (W m^{-2}), with λ being the heat of vaporization. In their simplest forms, H and E can be expressed as

$$H = \rho c_p(T_c - T_A)/r_a \qquad (2)$$

$$\lambda E = \rho c_p(e_c^* - e_A)/[\gamma(r_a + r_c)] \qquad (3)$$

where ρ is the density of air (kg m^{-3}), c_p the heat capacity of air (J kg^{-1} °C^{-1}), T_c the surface temperature (°C), T_A the air temperature (°C), e_c^* the saturated vapor pressure (Pa) at T_c, e_A the vapor pressure of the air (Pa), γ the psychrometric constant (Pa °C^{-1}), r_a the aerodynamic resistance (s m^{-1}), and r_c the canopy resistance (s m^{-1}) to vapor transport. A detailed discussion of procedures leading to (1)–(3) is given by *Monteith* [1973].

Combining (1), (2), and (3), assuming that G is negligible, and defining Δ as the slope of the saturated vapor pressure–temperature relation $(e_c^* - e_A^*)/(T_c - T_A)$, units of Pa °C^{-1}, we obtain

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma(1 + r_c/r_a)}{\Delta + \gamma(1 + r_c/r_a)} - \frac{e_A^* - e_A}{\Delta + \gamma(1 + r_c/r_a)} \qquad (4)$$

Paper number 1W0449.

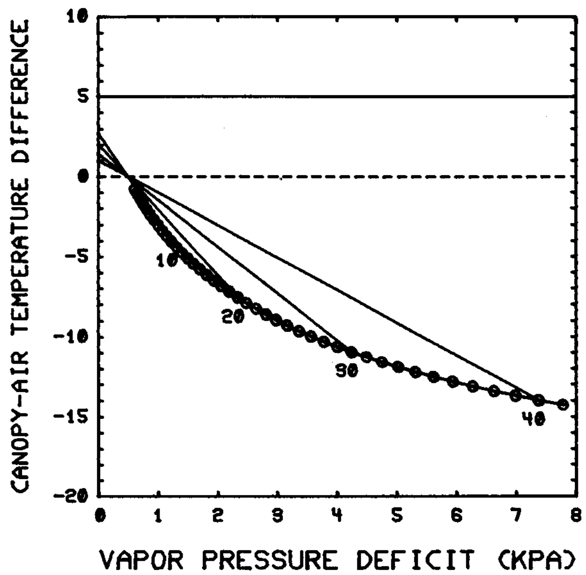

Fig. 1. Upper and lower bounds of the canopy-air temperature difference. The circles represent the lower bound for a particular temperature at the maximum vapor pressure deficit for that temperature. Numbers on the graph identify the temperatures (°C) for which the linear lines shown were calculated. The upper limit, represented by the horizontal line at $T_c - T_A = 5$, was calculated assuming $r_a = 10$ s m^{-1} and $R_n = 600$ W m^{-2}.

which relates the difference between the canopy and the air temperatures to the vapor pressure deficit of the air ($e_A^* - e_A$), the net radiation, and the aerodynamic and crop resistances.

The limits of $T_c - T_A$. The upper limit of $T_c - T_A$ can be found from (4) by allowing the crop resistance r_c to increase without bound, that is, as $r_c \to \infty$:

$$T_c - T_A = r_a R_n / \rho c_p \tag{5}$$

The lower bound, found by setting $r_c = 0$ in (4) (the case of wet plants acting as a free water surface), is

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma}{\Delta + \gamma} - \frac{(e_A^* - e_A)}{\Delta + \gamma} \tag{6}$$

Equations (4) and (6) describe a linear relation between $T_c - T_A$ and the vapor pressure deficit $e_A^* - e_A$. Thus for a particular temperature (see Figure 1) the lower bound is a line extending from the intercept at $e_A^* - e_A = 0$ (saturated air) to a value of $e_A^* - e_A = e_A^*$ (completely dry air). Since Δ appears in both the slope and the intercept, both terms are temperature dependent. Thus the lower bound is temperature dependent and is formed by a family of lines, one for each temperature. Lines for four temperatures, 10°, 20°, 30°, and 40°C are illustrated in Figure 1. The circles represent the endpoints of lines for temperatures incremented by 1° from 0° to 41°C.

The lower limit shown by the circles in Figure 1 is for a completely dry atmosphere, a situation not usually encountered. Also, in calculating this limit, various factors such as net radiation and resistance terms were held constant. In a natural situation the air is not completely dry, and the various environmental factors are all interrelated. Thus the curved lower limit shown in Figure 1 may not be encountered in practice, but a near-linear relation may obtain, as is observed experimentally by *Idso et al.* [1981*a*].

Potential evapotranspiration. Equation (6) represents the case of evaporation from a free water surface, which is not necessarily the case for potential evaporation from a crop. In irrigated areas the soil may be adequately supplied with water, with the plant surfaces being dry. In this case the canopy resistance is probably not zero [*van Bavel and Ehrler,* 1968] but has a value that we will call the canopy resistance at potential evapotranspiration (r_{cp}). The value of r_{cp} will probably be different for different crops and may change with crop variety. Setting $r_c = r_{cp}$ in (4), we have

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma^*}{\Delta + \gamma^*} - \frac{e_A^* - e_A}{\Delta + \gamma^*} \tag{7}$$

where

$$\gamma^* = \gamma(1 + r_{cp}/r_a) \tag{8}$$

An index of crop water status. A crop with adequate water will transpire at the potential rate for that crop. As water becomes limiting, the actual evapotranspiration will fall below the potential rate. A measure of the ratio of actual to potential evapotranspiration should therefore be an index of crop water status. Combining (1), (2), and (3) and solving for λE yields

$$\lambda E = \frac{\Delta R_n + \rho c_p (e_A^* - e_A)/r_a}{\Delta + \gamma(1 + r_c/r_a)} \tag{9}$$

which is the Penman-Monteith equation for evapotranspiration in terms of canopy and aerodynamic resistances [*Monteith,* 1973: *Thom and Oliver,* 1977]. Taking the ratio of actual (λE for any r_c) to potential (λE_p for $r_c = r_{cp}$) gives

$$E/E_p = \frac{\Delta + \gamma^*}{\Delta + \gamma(1 + r_c/r_a)} \tag{10}$$

with γ^* defined by (8). *Jensen* [1974] and *Howell et al.* [1979] discussed (10) for the case of $r_{cp} = 0$, that is, $\gamma^* = \gamma$. Rearranging (10) will give r_c in terms of E/E_p, a result reported by van Bavel [1967], *Szeicz and Long* [1969], and *Russell* [1980], again with $r_{cp} = 0$. Van Bavel measured E with lysimeters and calculated the canopy resistance.

The ratio E/E_p ranges from 1 (ample water, $r_c = r_{cp}$) to 0 (no available water, $r_c \to \infty$). In studying plant-water relations one thinks of a plant as going from a no-stress to a stressed condition. Therefore it is esthetically pleasing for a stress index to go from 0 to 1. Consequently, we define a crop water stress index (CWSI) as

$$\text{CWSI} = 1 - E/E_p = \frac{\gamma(1 + r_c/r_a) - \gamma^*}{\Delta + \gamma(1 + r_c/r_a)} \tag{11}$$

To calculate the CWSI or E/E_p using (10) or (11) requires a value for the ratio r_c/r_a. This is obtained by rearranging (4) with the result

$$\frac{r_c}{r_a} = \frac{\gamma r_a R_n/(\rho c_p) - (T_c - T_A)(\Delta + \gamma) - (e_A^* - e_A)}{\gamma[(T_c - T_A) - r_a R_n/(\rho c_p)]} \tag{12}$$

giving the ratio r_c/r_a in terms of net radiation, canopy and air temperatures, vapor pressure deficit, and the aerodynamic resistance. In practice, r_c/r_a is evaluated using (12) and substituted into (11) to obtain the CWSI.

The evaluation of Δ. The slope Δ of the saturated vapor pressure–temperature relation appears in most of the equations in the previous section. As a first approximation, Δ can be evaluated at the air temperature T_A. When the temperature difference ($T_c - T_A$) is large (for the case of well-watered crops

TABLE 1. Irrigation Dates and Amounts for Four Wheat Plots

Irrigation Date, 1980	Amount, m			
	Plot A	Plot B	Plot C	Plot D
Feb. 8 (39)	0.121	0.116	0.110	0.116
March 19 (79)		0.086		
April 2 (93)			0.100	
April 7 (98)				0.114
April 9 (100)	0.102			
April 15 (106)		0.101		
April 23 (114)			0.102	
April 28 (119)				0.099
May 2 (123)		0.102		
May 13 (134)		0.100		

*Numbers in parentheses indicate Julian dates.

at high vapor pressure deficits), a better approximation is to evaluate Δ at $(T_c + T_A)/2$. Obviously, when T_c is near T_A, the two approaches yield similar results. Taking the average of the canopy and air temperatures is sufficient for (4), (6), (7), and (12), but (10) and (11) pose a problem. Following closely the development of (10) from (9), we find that Δ in the numerator should be evaluated as the average of the air temperature and the canopy temperature that would obtain if the crop were evaporating at potential. The Δ in the denominator should be evaluated as the average of the actual measured canopy temperature and the air temperature. Keeping Δ as the value at the measured temperatures and Δ^* as the value using the calculated canopy temperature at potential, the numerator of (10) becomes $\Delta^* + \gamma^*$, and the numerator of (11) becomes $\gamma(1 + r_c/r_a) - \gamma^* + (\Delta - \Delta^*)$.

The evaluation of Δ^* is complicated by the fact that T_c at potential may not be known. This can be calculated using an iterative procedure with (7) by evaluating Δ at T_A, calculating T_c, evaluating a new Δ at $(T_c + T_A)/2$, and recalculating T_c until an acceptable value is obtained. In practice, the use of (10) and (11) with Δ evaluated at the average of the measured canopy temperature and the air temperature will yield similar results for both the low and the high values of the indices, with the maximum error occurring near 0.5. At the midpoint the difference between the two methods of calculation will be within 0.06, for example, 0.48 for the one value of Δ and 0.54 when Δ and Δ^* are used. The results reported here are in terms of Δ evaluated at the average of the measured canopy and air temperatures.

EXPERIMENTAL PROCEDURE

Four 11 × 13 m plots were planted to wheat (*Triticum durum* Desf. var. Produra) on February 6, 1980. The four level plots were flood irrigated on the dates and with the treatments shown in Table 1.

Canopy temperatures were measured with a portable infrared thermometer held at an angle of about 30° from horizontal. By the time the plants were about 20 cm tall (day 70), the instrument viewed predominately foliage when held at 30°. Plot canopy temperatures were taken as the average of eight measurements, four facing east and four facing west between 1340 and 1400 each day, except some weekends. Wet- and dry-bulb temperatures were measured with a psychrometer held at a height of 1.5 m. Incoming solar radiation was recorded every 20 min, each recording being an average of 15–20 scans made during the period. Net radiation was taken as 0.75 of the incoming solar radiation [*Fritschen,* 1967]. This approximation was used because, in practice, the stress index described here would require only an estimated value of net radiation (except for low vapor pressure deficit situations). Wind speed at the site was not obtained because of instrument malfunction.

Soil water contents were measured at 0.2-m intervals to a depth of 1.6 m 2–3 times per week. Water contents were smoothed using a sliding cubic technique briefly described by *Jackson et al.* [1977] (an adaptation of the sliding parabola of *DuChateau et al.* [1972]). The smoothing procedure allowed the interpolation of water contents for each day. The extractable water used was calculated using field-measured values of the upper and lower water content limits for each depth.

Data reported in the next section exclude only those days that caused intermittent sun/shade conditions during the time of measuremnts. The data represent days of complete cloud cover and days with clear skies. Winds were generally low except for a few gusty days. Vapor pressure deficits covered a wide range.

RESULTS AND DISCUSSION

Seasonal range of $T_c - T_A$. The canopy-air temperature difference measured on the wheat plots during the period of March 12, (day 72) to May 25 (day 145), 1980, are shown as a function of vapor pressure deficit in Figure 2. Also included are a few points from an earlier planting of wheat to provide more data in the low vapor pressure range. The horizontal line at $T_c - T_A = 5$ appears to adequately represent the upper limit for this crop. Assuming net radiation (R_n to be 600 W m^{-2}, the value of r_a is 10 s m^{-1}. Since R_n changed somewhat from day to day and during the season, it is to be expected that data plotted in this manner would show scatter. The lower limit, shown by the descending solid line, was calculated using (7) with $R_n = 600$ W m^{-2}, $r_a = 10$ s m^{-1}, and $r_{cp} = 5$ s m^{-1}.

The four wheat plots were part of a larger experiment and were planted 2–3 months later than normal planting dates for the Phoenix area. During April and May, temperatures were warm, and the wheat plants may not have been able to main-

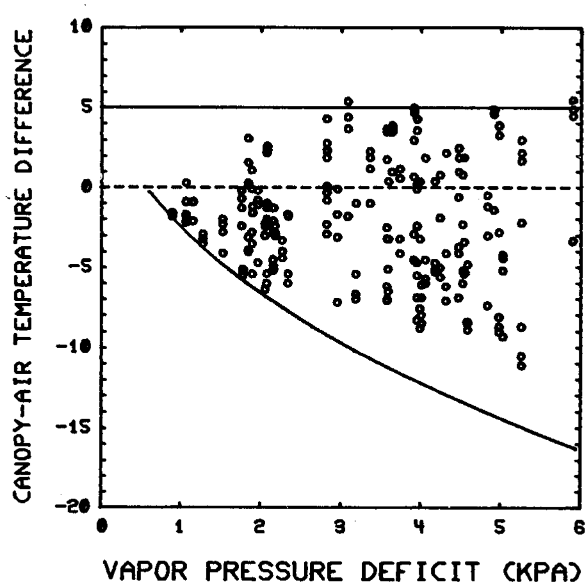

Fig. 2. Experimental data from four wheat plots in relation to the upper and lower bounds of the canopy-air temperature difference.

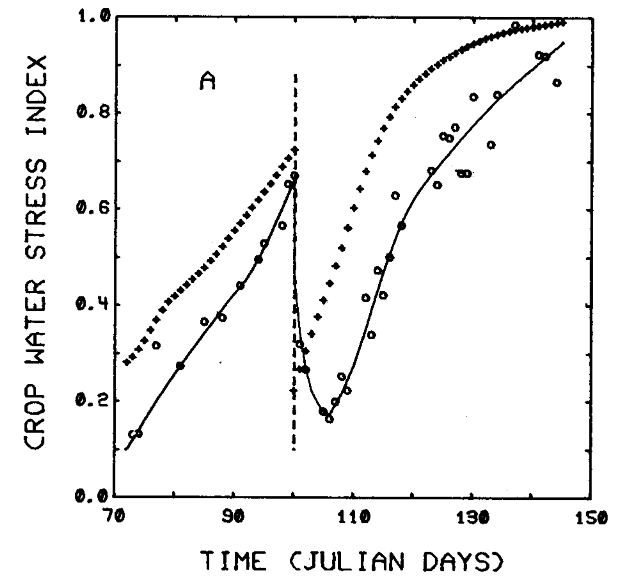

Fig. 3. Crop water stress index as a function of Julian days for plot A, which received a single postemergence irrigation. Circles represent the data points, and the solid line was drawn by eye to show the trend of the data points. The plus symbols represent the extractable water used from the 0- to 1.1-m depth. Values on the ordinate also represent extractable water used.

tain the theoretical potential evapotranspiration rate. This is suggested by data for vapor pressure deficits of 3 kPa and greater.

The crop water stress index. The crop water stress indices for the four plots are given as functions of time (from day 72 to day 145) in Figures 3–6. The circles represent CWSI values calculated using (11). (In the calculations, r_{cp} = 5 s m^{-1} was used. The choice of this value is discussed in the section on resistance terms.) The solid lines were drawn by eye through the data points. The plus symbols represent smoothed and interpolated values of extractable water used from the 0- to 1.1-m depth. The vertical dashed lines in the four figures indicate the days that the plots were irrigated.

Plot A (Figure 3) received an irrigation on day 100, the latest for the four plots (making plot A the most stressed). Beginning on day 72, the CWSI increased with time, reaching a value of 0.67 before irrigation. After irrigation the CWSI did not drop immediately to zero but decreased to a minimum on day 106. The 5–6 days required to reach a minimum appear to be necessary to allow the plant to recover from a stressed condition. Dried and curled leaves need to be rehydrated, and roots previously in dry soil would need time to grow new root hairs to be able to extract soil water at a near-potential rate. A similar recovery period was documented for cotton by *Ehrler* [1973] and for sorghum by *Idso and Ehrler* [1976].

The nominal amount of irrigation water applied was 0.1 m (see Table 1 for metered amounts), not sufficient to completely replace the amount of water extracted. This is evident from soil water data and from the fact that the CWSI did not decrease much below 0.2 after irrigation.

Figure 4 shows data for plot B, the wettest plot. This plot received four irrigations during the measurement period (Table 1). The irrigation on day 79 (which nearly replaced the extracted water) occurred while the plants were vigorously growing and not stressed. Apparently, no recovery time is necessary under these conditions. The only time we were reasonably confident that the plants were transpiring at the potential rate was after this irrigation.

The three subsequent irrigations for plot B all showed that several days recovery time was necessary to approach maximum transpiration (minimum CWSI). The last three irrigations did not adequately replace the extracted water. The final irrigation, given well after heading, was not beneficial to the plants. Senescence had progressed to the point that the added water had little effect on plant transpiration (and thus plant temperature).

Plots C and D (Figures 5 and 6) each received two irrigations but at different times. In general, the earlier irrigations (plot C) caused lower values of the CWSI. A recovery period is evident for both irrigations on the two plots.

The CWSI was measured well beyond the time that the final irrigation would be given. By day 145 the plants were completely senesced (except perhaps in plot B). The data points for the CWSI greater than 0.8 show more scatter than for lower values. At this stage, plant temperatures were warmer than air temperatures, and convection cells were operating, causing considerable fluctuation of the measured plant temperatures. Fortunately, this condition occurs during the least interesting and least essential times, when the crop is nearing complete senescence.

Extractable water. Except for the postirrigation recovery periods the extractable water used and the CWSI follow nearly, but not precisely, parallel paths. This is evidence for close coupling of soil water and plant temperatures and thus provides strong support for the use of plant temperatures to evaluate plant water stress. Observation of the data in Figures 3–6 tempts one to plot the CWSI as a direct function of extractable soil water. However, such a plot does not show a unique relationship between the two variables for several reasons. To obtain a unique relation, it would be necessary to accurately specify the volume of soil within which the roots were actively taking up water. This volume continuously changes as the roots grow. We can show the extractable water only for a fixed volume. In addition, the CWSI is dependent upon the evaporative demand. For example, if the evaporative demand exceeds the ability of the roots to take up water, or water to

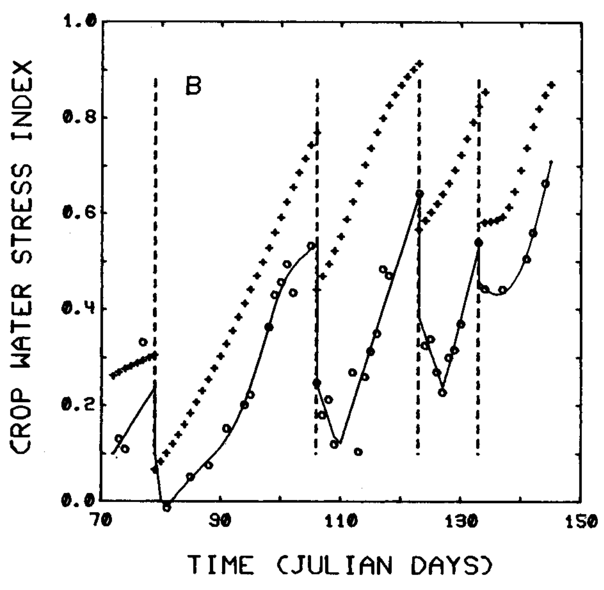

Fig. 4. Same as Figure 3, for plot B, which received four postemergence irrigations.

move to the roots, the CWSI could increase without a corresponding increase in extractable water used. The CWSI-extractable water relationship is discussed in detail by *Jackson* [1981].

The resistance terms. We evaluated r_a for wheat by measuring $T_c - T_A$ and R_n for a mature, fully senesced wheat crop (with no available soil water) and solving (5) for r_a. Measurements involved monitoring one area with a fixed position 15° FOV infrared thermometer and a hand-held 2.5° FOV instrument. The stationary instrument was automatically scanned every 6 s, with these values averaged over a 6-min period. With the hand-held instrument, 6–8 instantaneous measurements were made over different parts of the field. In both cases the average temperature difference was 5°C. The range of differences was from 2° to 9°C. This range of temperatures is due to convection cells within the canopy. By holding a radiometer stationary, $T_c - T_A$ values were observed to increase until a value of about 9°C was reached then rapidly drop to about 2°C. During the measurements the wind speed was low (1 m s^{-1} or less). The incoming radiation was high ($\simeq$800 W m^{-2}), and air temperatures were >35°C, conditions conducive to high canopy temperatures. Since the average value of $T_c - T_A$ was 5°C under these conditions, it appears that this value may be near the maximum that can be expected. Using this value in (5) we find $r_a = 10$ s m^{-1}, with the conclusion that this value may be near its maximum also.

Idso et al. [1981*b*] obtained $T_c - T_A$ and $e_A^* - e_A$ data for well-watered alfalfa fields located in Arizona, Kansas, Minnesota, and Nebraska and for a stressed alfalfa field in Arizona. The intercept of a $T_c - T_A$ versus $e_A^* - e_A$ plot was about 1°C. Since r_c was finite, (5) does not apply, but the first term on the right-hand side of (6) can be used to estimate r_a. The resulting value is 6 s m^{-1}. We conclude that a likely value for r_a lies between 6 and 10 s m^{-1} and that this value is relatively constant. From an operational point of view, a value of $r_a = 10$ s m^{-1} appears reasonable.

A value of $r_{cp} = 5$ s m^{-1} was determined by adjusting r_{cp} until a CWSI value near 0 was obtained for the first irrigation shown on plot B (Figure 4). This was essentially a one-point fit; consequently, its applicability is questionable. However, subsequent experiments with alfalfa and cotton have shown this value to be a reasonable first approximation. We have used this term as a constant. It is more likely different for different crops and probably changes with time as the crop matures. Environmental factors may cause it to be time-of-day dependent. Obviously, more experimental data are needed. Such data, however, should be from areal measurements of crop canopies (in contrast to individual leaves) to assure application to an operational system that uses infrared thermometers to rapidly assess crop water stress.

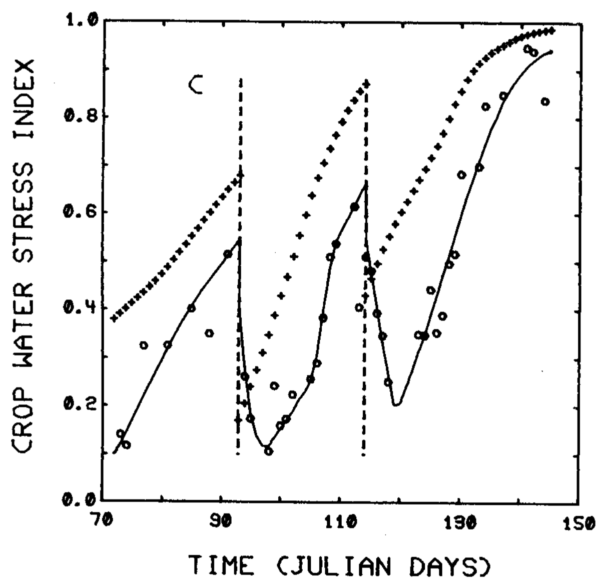

Fig. 5. Same as Figure 3, for plot C, which received two post-emergence irrigations.

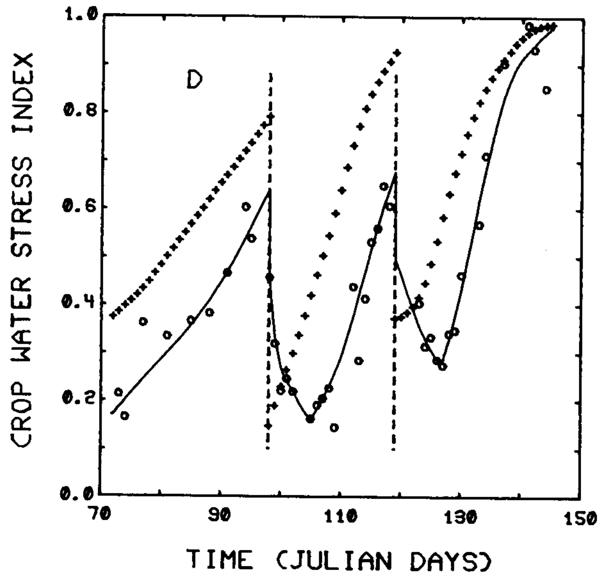

Fig. 6. Same as Figure 3, for plot D, which received two post-emergence irrigations on dates different from those in Figure 5.

Sources of error. There are several environmental and instrumental factors that can cause errors in the CWSI calculation. Wind is a major environmental factor that does not explicitly appear in (12). It is, however, implicit in that it affects the aerodynamic resistance r_a. *Thom and Oliver* [1977] derived a wind function in terms of r_a for the Penman-Monteith equation. Calculations using their equation lead to the qualitative conclusion that an increase in wind speed would cause an increase in the CWSI. For a well-watered crop, with representative values of R_n, T_A, and VPD, the CWSI would be 0.07 and 0.15 for wind speeds of 2 and 10 m s^{-1}, respectively.

Rapidly changing cloud conditions can cause serious errors in the CWSI measurement, especially if the air temperature is measured a few minutes before or after the canopy temperature measurements. Shaded and sunlit canopies can exhibit different temperatures. The net radiation estimate under such conditions may be poor. We recommend that data not be taken under these conditions unless all measurements can be made essentially instantaneously. Measurements can be made if conditions are relatively constant, either clear or cloudy. As an example, on day 114, overcast conditions prevailed, R_n was about 220 W m^{-2}, yet the CWSI exhibited no more scatter than on any other day.

Errors in measurement of the wet-bulb and dry-bulb temperatures can cause errors in the CWSI. The dry-bulb temperature T_A forms a part of $T_c - T_A$ and enters in the calculation of $e_A^* - e_A$; thus an error in T_A will cause a greater error in the CWSI than an error in the wet-bulb measurement, because the latter appears only in the $e_A^* - e_A$ calculation. An error in T_c will cause the same error in the CWSI as T_A, less the effect on $e_A^* - e_A$.

Errors in the canopy temperature measurement may occur because of inadequate calibration of the instrument, because of a wrong estimate of emissivity, or because non-representative portions of the field are included in the field of view of the instrument. The emissivity of a plant canopy is nearly 1. Emissivities of plant leaves are about 0.97–0.98 [*Idso et al.*, 1969]. A canopy as seen by an infrared thermometer includes leaves and cavities formed by the canopy architecture that closely approximate blackbodies. In our calculations we used an emissivity of 1, recognizing that the true value may be slightly less.

It is important that the soil background not appear in the field of view of the infrared thermometer. Soil temperatures can be drastically different from plant temperatures, and their inclusion can cause serious errors in the CWSI.

Concluding Remarks

The CWSI is a promising tool for the quantification of crop water stress. It is an essentially instantaneous measurement in that an area of a field can be rapidly scanned with an infrared thermomenter, wet- and dry-bulb air temperatures measured, and net radiation estimated, in minutes. Calculations are straightforward using a hand calculator or a computer. Measured data are entered in (12), and r_c/r_a is calculated and substituted into (11) to obtain the CWSI. A microprocessor could be developed to field process the data and provide immediate values of the CWSI.

The use of the CWSI in irrigation-scheduling schemes requires further research to determine the CWSI value at which irrigation should be applied. This may vary with crops. The CWSI may not be a sufficient indicator of irrigation needs for crops such as potatoes that receive frequent irrigations to keep the top soil moist for tuber growth. For other crops, such as grains and alfalfa, it may prove useful as an irrigation guide.

Acknowledgments. Helpful discussions with A. Perrier, Station de Bioclimatologie, Versailles, France, are gratefully acknowledged. Contribution from the Agricultural Research, Science and Education Administration, U.S. Department of Agriculture.

References

DuChateau, P. C., D. L. Nofziger, L. R. Ahuja, and D. Swartzendruber, Experimental curves and rates of change from piecewise parabolic fits, *Agron. J., 64,* 538–542, 1972.

Ehrler, W. L., Cotton leaf temperatures as related to soil water depletion and meteorological factors, *Agron. J., 65,* 404–409, 1973.

Fritschen, L. J., Net and solar radiation relations over irrigated field crops, *Agric. Meteorol., 4,* 55–62, 1967.

Gates, D. M., Leaf temperature and transpiration, *Agron. J., 56,* 273–277, 1964.

Howell, T. A., W. R. Jordan, and E. A. Hiler, Evaporative demand as a plant stress, in *Modification of the Aerial Environment of Plants, Monogr. 2,* edited by B. J. Barfield and J. F. Gerber, pp. 97–113, American Society of Agricultural Engineers, St. Joseph, Mich., 1979.

Idso, S. B., and W. L. Ehrler, Estimating soil moisture in the root zone of crops: A technique adaptable to remote sensing, *Geophys. Res. Lett., 3,* 23–25, 1976.

Idso, S. B., R. D. Jackson, W. L. Ehrler, and S. T. Mitchell, Infrared emittance determination of leaves, *Ecology, 50,* 899–902, 1969.

Idso, S. B., R. D. Jackson, and R. J. Reginato, Remote sensing of crop yields, *Science, 196,* 19–25, 1977.

Idso, S. B., R. D. Jackson, P. J. Pinter, Jr., R. J. Reginato, and J. L. Hatfield, Normalizing the stress-degree-day parameter for environmental variability, *Agric. Meteorol.,* in press, 1981*a*.

Idso, S. B., R. J. Reginato, D. C. Reicosky, and J. L. Hatfield, Determining soil induced plant water potential depressions in alfalfa by means of infrared thermometry, *Agron. J.,* in press, 1981*b*.

Jackson, R. D., Soil moisture inferences from thermal infrared measurements of vegetation temperatures, in *Digest 1981 International Geoscience and Remote Sensing Symposium, Washington, D. C.,* Institute of Electrical and Electronic Engineers, New York, in press, 1981.

Jackson, R. D., R. J. Reginato, and S. B. Idso, Wheat canopy temperature: A practical tool for evaluating water requirements, *Water Resour. Res., 13,* 651–656, 1977.

Jensen, M. E. (Ed.), *Consumptive Use of Water and Irrigation Water Requirements,* 215 pp., American Society of Civil Engineers, New York, 1974.

Monteith, J. L., *Principles of Environmental Physics,* 241 pp., Edward Arnold, London, 1973.

Monteith, J. L., and G. Szeicz, Radiative temperature in the heat balance of natural surfaces, *Q. J. R. Meteorol. Soc., 88,* 496–501, 1962.

Russell, G., Crop evaporation, surface resistance and soil water status, *Agric. Meteorol., 21,* 213–226, 1980.

Szeicz, G., and I. F. Long, Surface resistance of crop canopies, *Water Resour. Res., 5,* 622–633, 1969.

Tanner, C. B., Plant temperatures, *Agron. J., 55,* 210–211, 1963.

Thom, A. S., and H. R. Oliver, On Penman's equation for estimating regional evaporation, *Q. J. R. Meteorol. Soc., 103,* 345–357, 1977.

Van Bavel, C. H. M., Changes in canopy resistance to water loss from alfalfa induced by soil water depletion, *Agric. Meteorol., 4,* 165–176, 1967.

Van Bavel, C. H. M., and W. L. Ehrler, Water loss from a sorghum field and stomatal control, *Agron. J., 60,* 84–86, 1968.

Wiegand, C. L., and L. N. Namken, Influence of plant moisture stress, solar radiation, and air temperature on cotton leaf temperatures, *Agron. J., 58,* 582–586, 1966.

(Received November 14, 1980;
revised March 6, 1981;
accepted March 12, 1981.)